Life Cycle Analysis (LCA) Report

Hydrogen Fuel Production with Tri-Gen DFC® from Anaerobic Digestion of Wastewater Sludge

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1. INTRODUCTION

FuelCell Energy, Inc. (NASDAQ: FCEL) is an integrated fuel cell company with an expanding global presence on three continents. We design, manufacture, sell, install, operate and maintain ultra-clean, highly efficient stationary fuel cell power plants (DFC®) for distributed power generation. Our DFC® plants provide megawatt-class scalable on-site power and utility grid support, helping customers solve their energy, environmental and business challenges. Our plants are operating in more than 50 locations on three continents and have generated more than four billion kilowatt hours (kWh) of ultra-clean power. In addition to power and thermal energy, our DFC® plants produce excess hydrogen which can be separated, purified and compressed to meet hybrid hydrogen fuel cell vehicles standards (refered to as trigeneration, or Tri-Gen because of the production of power, heat, and hydrogen).

The first Tri-Gen DFC® system was installed at the Orange County Sanitation District in Fountain Valley California. The plant produced electricity, hydrogen and thermal energy from 2011 to 2014 using onsite biomethane produced from anaerobic digestion of wastewater sludge. The report "Validation of an Integrated Hydrogen Energy Station" (October 2012) provides a detailed description of all the lessons learned during the three years of operation. After the completion of the Fountain Valley project, the technology is being introduced in commercial MW-scale systems which will generate 1,270 kg/day, 2,250kW of electric power and 2MMBTU of thermal energy. Electric power and thermal energy will be used for the wastewater treatment plant operation whereas the hydrogen produced will be distributed to the nearby hydrogen stations following the hub and spoke distribution model. Average transportation distance is estimated to be 30 miles.

2. FEEDSTOCK ORIGIN AND SUPPLY

Methane rich gas produced via 1-stage mesophilic anaerobic digestion of wastewater sludge (i.e., anaerobic digester gas (ADG) will be converted to electricity, thermal and hydrogen with a DFC® fuel cell system).

ADG contains contaminants that must be removed before the ADG can be used as a fuel source for generating syngas. It is difficult to remove these contaminants, which include siloxanes, hydrogen sulfide, methanol and ammonia. Siloxanes are a family of chemical compounds also known as organosilicons that can seriously damage all forms of generation systems. Widely used in toiletries and cosmetics, siloxanes find their way into municipal wastewater streams and are not broken down during the anaerobic digestion process.

Subsequently, the fuel cell power plants operating on ADG require a fuel treatment system that typically uses graphite carbon-based filter media with pore structures specially designed to remove siloxanes. In conjunction with this pre-treatment method, hydrogen sulfide (H2S) is also extracted using a catalytic iron sponge system. Residual oxygen is removed by either a carbon bed or a deoxidizer reactor, depending on the specific ADG analysis. Other methods are used to eliminate ammonia, methanol and excess humidity from the ADG stream.

3. TRI-GEN DFC® PROCESS OVERVIEW

Figure 1 shows the process flow diagram of the Tri-Gen DFC® system.

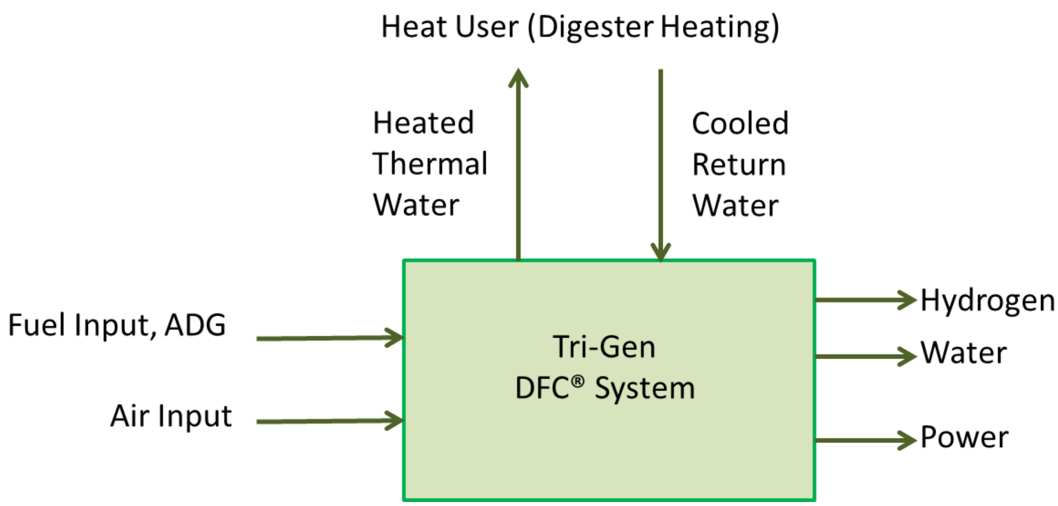

Figure 1 Tri-Gen DFC Process Flow Diagram

Hydrogen is produced via internal reformation which is an endothermic process. Heat driving internal reformation comes from the exothermical fuel cell electrochemical reactions to produce electricity, water and CO_2. This uniqueness of Tri-Gen DFC® system is that hydrogen could never be produced without the electricity generation from the fuel cell. Therefore, one cannot think of the Tri-Gen system as a reformer that yields hydrogen, plus a hydrogen fuel cell that generates electricity and a potential hydrogen stream that depends on how much electricity we decide to generate. Without the heat from the exothermic fuel cell reactions we wouldn't be able to reform the hydrogen produced for transportation.

Internal Reformation (Endothermic):

CH4 + 2H2O → 4H2 + CO2

Electrochemical Fuel Cell Reactions (Exothermic):

$H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2e^-$ (Anode)
$\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{-2}$ (Cathode)

4. TRI-GEN DFC® MASS BALANCE (THEORETICAL)

Heat and mass balance of the Tri-Gen DFC® is shown in Table 1 and Table 2. Although it may be irrelevant for the purpose of this report, it is important to note that Tri-Gen DFC® systems are positive water generator which is important to consider under current California severe drought.

Table 1 Tri-Gen DFC Heat Mass Balance Summary

Power Output:		
Gross DC	3,078	kW
Gross AC	2,955	kW
Parasitic	705	kW
Net AC at 13.8 KV	2,250	kW
Fuel Input, LHV, kW	6,577	kW
Fuel Input, LHV, MMBtu/h	22.45	MMBtu/h
Hydrogen production	1,270.00	kg/day
Thermal output	2.00	MMBtu/h

Table 2 Tri-Gen DFC Heat Mass Balance Detailed

	Fuel Input	**Air Input**	**System Exhaust**	**Hydrogen**	**Water Produced**	**Thermal Return Water Input**	**Thermal Water to Heat User**
Molar flow lbmol/hr	108.4	632.4	673.9	57.9	48.0	5550	5550
Mass flow lb/hr	2951	18176	20326	117	865	100011	100011

5. PATHWAY METHODOLOGY

To calculate the carbon intensity of the Tri-Gen DFC® Pathway we considered the entire wastewater treatment plant (WWTP) as a system boundary. We used GREET Model to estimate the electricity and thermal demands of the WWTP as well as the biogas production via anaerobic digestion of wastewater sludge.

Electricity and thermal demands for plant operations are met with the electricity and thermal energy produced on-site with the DFC® and existing CHP engines which are fueled with excess biogas. Excess electricity is credited as a Surplus Electricity Available for Export using CAMX.

5.1. ANAEROBIC DIGESTER GAS PRODUCTION

Table 3 shows the key assumptions used for the biogas production via Anaerobic Digestion.

Table 3 Key Assumptions regarding Wastewater Treatment Sludge-based Anaerobic Digestion

Location	CA	
Reactor Size	120 MGD	
Reactor Type	Meso - 1 stage	
Holding duration in digested sludge holding tanks	5 days	
Storage duration in dewatered biosolids storage tanks	1 day	

Since the GREET model doesn't allow reactor sizer larger than 100MGD, we modeled the plant using 100MGD and then extrapolating the results to 120MGD as shown in Table 4:

Table 4 Biogas production results with GREET model

"RNG" Modeled Biogas Produced (100 MGD)	53,178	m3/day
"RNG" Modeled CH4 Produced (100 MGD)	33,236.17	m3/day
"RNG" Modeled Energy Available	1,191,158.34	MJ/day
"RNG" Thermal Energy Required	412,933.00	MJ/day
"RNG" Electrical Energy Required	124,892.00	MJ/day
OCSD Biogas Produced (120 MGD):	63,813.44	m3/day
OCSD CH4 Produced (120 MGD):	39,883.40	m3 CH4/day
OCSD Energy Available:	1,429,390	MJ/day
OCSD Biogas Available:	1,564.79	scfm biogas
OCSD CH4 Available:	977.99	scfm CH4

5.2. TRI-GEN EMISSIONS

Emissions from the Tri-Gen system are shown in Table 5,

Table 5 Carbon Emissions from Tri-Gen

Digester Biogas Allocated to FCE:	685.48	scfm biogas
Digester Biomethane Allocated to FCE	428.43	scfm CH4
Digester Biomethane Allocated to FCE	24.73	mmBtu / hr
Digester Biomethane Allocated to FCE	616,932.00	scf/day
Process CH4 + O2 --> CO2 + 2.H2	1,718.47	lb-mol CH4
Therefore, CO2 emissions / day	1,718.47	lb-mol CO2
Therefore, CO2 emissions / day	**34,297,982.25**	**g CO2e/day**

5.3. CHP EMISSIONS

Excess biogas is used at a CHP engine plant to co-generate electricity and thermal energy.

Excess biogas = (1546.8 – 685.5) = 549.6 scfm

Emissions from the CHP engines are shown in Table 6.

Table 6 Emissions from CHP Engines

	Emissions	
VOC	316,662.30	
CO	843,838.89	
NOx		
PM10		
PM2.5		
SOx		
CH4	7,467,540.41	
N2O	25,182.49	
CO2	43,248,895.88	
TOTAL	**51,902,119.97**	**g CO2e/day**

5.4. FUGITIVE EMISSIONS

Fugitive methane emissions from Wastewater Sludge Management have been also modeled and taken into consideration. According to the GREET Model, total fugitive emissions are:

Fugitive Emissions = **26,665,076.21 g CO2e/day**

5.5. H_2 COMPRESSOR AND REFUELING EMISSIONS (T&D)

Hydrogen is delivered at the Tri-Gen DFC® plant at 2600psia. The first compression stage after the Tri-Gen plant compresses hydrogen from 2600psia to tube-trailer pressure of 7000psia. Hydrogen is transported with a diesel truck from the Tri-Gen plant to the hydrogen station which is located at 30 miles. Hydrogen is stored at the station where pressure is boosted to delivery pressures of 12000psia to fill the 10000psia storage tanks of fuel cell vehicles. Compression after the Tri-Gen is assumed to be done with California Mix electricity.

Table 7 shows the GREET assumptions and results for the compression of hydrogen from the Tri-Gen plant to the vehicle tank.

Table 7 Hydrogen Compression from GREET

	H2 Compressor to Load Tube-Trailer	**H2 Compressor at Refueling Station (for Tube-Trailer Distribution)**	**H2 Compressor at Refueling Station (Distributed Production)**
Inlet Pressure [psia]	2,600	4,443	7,000
Outlet Pressure [psia]	**7,000**	**12,000**	**12,000**
Inlet Temperature [oF]	70	70	70
Specific Heat Ratio	1.40	1.40	1.40
Compression Ratio per Stage	2.1	2.1	2.1
Number of Compression Stages	2	2	1
Compressor Adiabatic Efficiency	80.0%	65.0%	65.0%
Compressibility Factor (z)	1.21	1.36	1.42
Theoritical Energy [kWh/kg]	0.4	0.5	0.3
Shaft Energy [kWh/kg]	0.55	0.76	0.43
Electric Motor Efficiency	92.0%	92.0%	92.0%
NG Engine Efficiency	35.0%	35.0%	35.0%
Electric Energy [kWh/kg]	0.59	0.82	0.47
NG Energy [kWh/kg]	1.56	2.17	1.24
Compression Efficiency (Electric)	95.9%		98.6%
Compression Efficiency (NG Engine)	89.9%		96.4%

The carbon impact associated with the compression process is **866,833.61 gCO2/day.**

5.6. AVOIDED FLARE - CREDIT

For purposes of reference scenario calculations it is assumed that in absence of the Tri-Gen DFC® project, the biogas would be flared. Therefore, the quantity of biogas flared is a "credit" for Avoidance of Flaring Emissions. These emissions are shown in Table 8.

Table 8. Emission "credit" for flaring avoidance

CH4 Available	978 scfm	Avoided Flaring Emissions
CH4 Generating Potential	**1,408,311**	**scf/day**
VOC	3,386.99	10,567.40
CO	35,224.67	55,302.73
CH4	66,384.95	1,659,623.87
N2O	1,490.27	444,101.81
CO2 from CH4 combustion	80,243,536.90	80,243,536.90
Total GHG Emissions		**82,413,132.72 gCO2e/day**

5.7. ELECTRICITY DISPLACED – CREDIT

It has been assumed that the surplus electricity from the CHP engines is available for export so it has been considered as "credit". T&D losses have been assumed to be 6.5%. Total credit for exporting excess power is:

Total Electricity Co-Product Credit	**32,041,889.09 g CO2e/day**

5.8. PATHWAY CARBON INTENSITY AGGREGATION

Table 9,

Table 10 and Table 11 show the total emissions, credits and aggregated emissions of the Tri-Gen DFC® Pathway.

Table 9 Emissions (gCO2e/day)

FCE Process Emissions (g CO2e/day)	IC Engine Combustion Emissions (g CO2e/day)	H2 COMPRESSOR AND REFUELING EMISSIONS (T&D) (gCO2e/day)	Est Fugitive CH4 (gCO2e/day)
34,297,982.25	51,902,119.97	866,833.61	26,655,076.21

Table 10 Emission Credits (gCO2e/day)

AVOID FLARE CREDIT (gCO2e/day)	ELECTRICITY DISPLACEMENT CREDIT (gCO2e/day)
82,413,132.72	32,041,889.09

Table 11 Aggregated Carbon Emissions (gCO2e/day)

TOTAL	
(733,009.77)	**gCO2e/day**

Total process hydrogen yield at the Tri-Gen DFC® plant corresponds to 748,240 MJ/day.

Therefore, the hydrogen carbon intensity with this new pathway is:

Table 12 Pathway Carbon Intensity

Fuel CI:	**(0.98)**	**gCO2e/MJ**